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EFFECT OF INTERNAL PRESSURE ON FLEXIBILITY AND STRESS INTENSIFICATION FACTORS
FOR PIPE ELBOWS ANALYZED BY THE FINITE ELEMENT METHOD

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Bethesda, Maryland 20084



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by

Antonio J. Quezon

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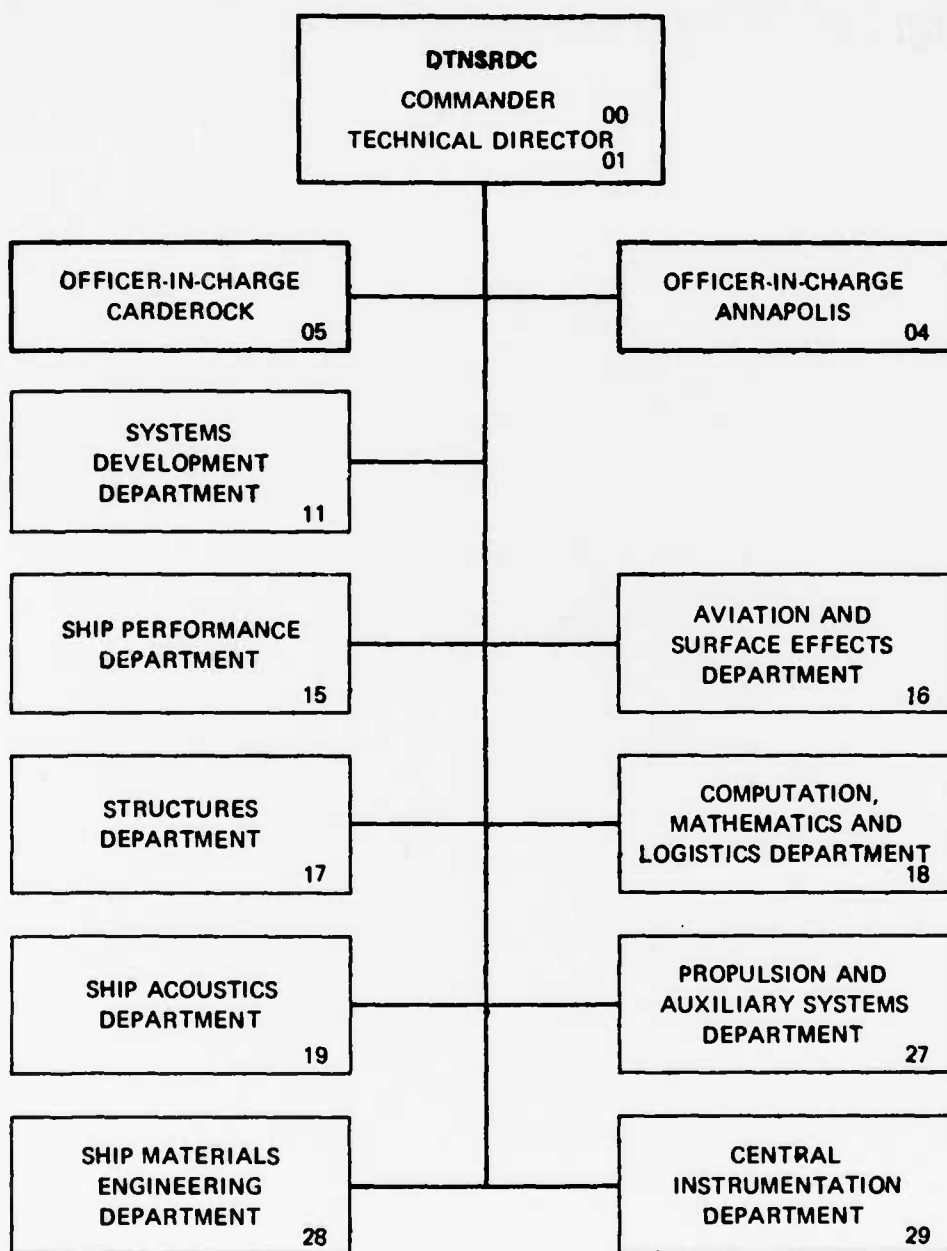
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ABSTRACT

A finite element analysis using NASTRAN was conducted on a 90-degree piping elbow subjected to an inplane bending load and internal pressures of 0, 400, and 800 psi. The objective of this study was to verify that the nonlinear effect of the superposition of internal pressure with inplane bending could be accounted for by employing a static analysis with differential stiffness. Flexibility factors and stress intensification factors were computed from the NASTRAN results. These numerical data were then compared to similar data obtained from experimental results.

The flexibility factors and stress intensification factors computed from the NASTRAN results were found to agree reasonably well with the experimental data. The NASTRAN values tended to be conservative in that they slightly overestimated the flexibilities and stresses. These differences might be attributed to such experimental factors as nonuniform pipe wall thickness, spacing of strain gages, and bending of tangent straight pipe extensions. In general, it is concluded that the differential stiffness capability in NASTRAN is adequate for accounting for the effects of internal pressure on flexibility factors and stress intensification factors.

ADMINISTRATIVE INFORMATION

This work was performed under the Naval Sea Systems Command Operational Systems Development Program "NSSN Noise Transmission Control," Program Element 25634N, Task Area S0218AS020, Task 20405 and Work Unit 2740-405. Naval Sea Systems Command cognizant program manager is Mr. R. Biancardi (NAVSEA 55N).

INTRODUCTION

Curved pipe and piping elbows are known to be more flexible and to have higher stresses than straight pipe of the same cross section. This difference is due to the tendency of an elbow cross section to flatten or "ovalize" upon bending, relieving longitudinal bending stresses in the extreme fibers and at the same time shifting maximum stresses nearer to the neutral axis. This shifting of the bending-stress distribution results in a decrease in the bending-moment resistance of the section. In the design and analysis of piping systems, flexibility factors and stress intensification factors, which are ratios of actual displacement and

stress to those predicted by elementary beam theory for straight pipe, are applied to account for the increase in displacement and stresses. The recommended factors are often based on elementary theoretical expressions or limited empirical data. Often the expressions for these factors include simplifying assumptions, such as long straight pipe extensions tangent to the elbow end to avoid interaction effects, or bending loads applied in the absence of internal pressure.^{1*}

Rodabaugh and George² presented theoretical equations for flexibility factors and stress intensification factors that included the effects of internal pressure for elbows with infinitely long tangent straight pipe extensions (i.e., no end interaction effects). Their equations were extended from the energy methods of von Karman³ and Vigness.⁴ Dodge and Moore⁵ in turn programmed a modified version of these equations to perform a parameter study on pressurized elbows subjected to inplane and out-of-plane bending.

Previous studies⁶ have validated the use of the finite element method for the prediction of the linear static behavior of piping elbows. The versatility of the finite element method also allows for the consideration of end interaction effects (boundary restraints) and various geometries (bend angle, bend radius, etc.). Quezon and Everstine⁷ conducted a finite element method parameter study of 90-degree elbows of various geometries to consider the effects of end restraints. The results of that study were combined with similar data for 45- and 180-degree elbows to form a data base for a computer program⁸ that computes flexibility factors and stress indices for Inconel 625 elbows. Neither of the latter two studies considered internal pressure in combination with other loads, since to do so would introduce another parameter. Also, it was not certain at the time that the finite element method could accurately represent the nonlinear effect of combining internal pressure and bending. It is known that combining internal pressure and bending results in reduced flexibilities and stresses since the tendency of an elbow to ovalize upon bending is counteracted by the internal pressure. For relatively thick-walled pipe under low stress conditions, this effect is insignificant; however, in the case of thin-walled pipe (e.g., Inconel 625) under high stresses, the effect of internal pressure becomes significant.

* A complete list of references is given on page 12

This report presents the results of a finite element method analysis of a 90-degree pipe elbow subjected to inplane bending in combination with internal pressures of 0, 400, and 800 psi. These results are then compared to experimental data published by Rodabaugh and George.⁷ The purpose of the work is to verify that the nonlinear effects of combining pressure and bending loads can be properly handled by the differential stiffness approach available in NASTRAN.

DEFINITIONS

The flexibility factor k for a piping component (such as an elbow or tee) is defined as the ratio of a relative rotation of that component to a nominal rotation:

$$k = \theta_{ab} / \theta_{nom} \quad (1)$$

where θ_{ab} = rotation of end "a" of the piping component relative to end "b" of that component due to a moment loading M , and in the direction of M

θ_{nom} = nominal rotation of an equal length of straight pipe due to the moment M

For elbows, the nominal rotation is computed using beam theory, in which case

$$\theta_{nom} = ML/EI \quad (2)$$

for inplane and out-of-plane bending moments, and

$$\theta_{nom} = ML/GJ \quad (3)$$

for torsional moments, where

M = applied moment load

L = arc length of centerline of elbow ($\approx \alpha R$)

R = elbow bend radius

α = bend angle in radians

E = Young's modulus of material

G = shear modulus of material

I = moment of inertia of cross section

J = torsional constant of cross section (equal to the polar moment of inertia for circular cross sections)

When computing the flexibility factor of a pressurized elbow, the rotation due to the internal pressure is not considered; hence the flexibility factor is given by

$$k = (\theta_{ab} - \theta'_{ab})/\theta_{nom} \quad (4)$$

where θ_{ab} and θ_{nom} are as previously defined and θ'_{ab} is the rotation of end "a" of the elbow relative to end "b" of the elbow due to the corresponding internal pressure loading.

The stress intensification factor c for an elbow is the ratio of the computed stress to a nominal stress

$$c = \sigma/\sigma_{nom} \quad (5)$$

where σ_{nom} is the nominal stress for the corresponding straight pipe as predicted by beam theory

$$\sigma_{nom} = M/z \quad (6)$$

where z is the section modulus of the pipe cross section.

In the computation of stress intensification factors for pressurized elbows, the stresses due solely to the internal pressure are subtracted from the total stress. Hence, the circumferential stress intensification factor for a pressurized elbow is given by

$$c = (\sigma_{\text{circ}} - Pr/t) / \sigma_{\text{nom}} \quad (7)$$

and the longitudinal stress intensification factor by

$$c = (\sigma_{\text{long}} - Pr/2t) / \sigma_{\text{nom}} \quad (8)$$

where P is the applied internal pressure, r is the mean pipe radius, and t is the pipe wall thickness.

When the bending is due to a force F applied at the free end of the straight pipe extension, the moment M in Equations (2) and (6) is computed by

$$M = FL \quad (9)$$

where L is the length of the tangent straight pipe extension at the free end.

STATEMENT OF PROBLEM

The elbow to be analyzed is a 30-in. outside diameter (O.D.), 0.500-in. nominal wall thickness, 90-degree welding elbow with a 45-in. bend radius. The average wall thickness of the elbow is 0.515 in. with variation of +0.058 in. and -0.094 in. The average O.D. is 29.973 in. with variation of +0.160 in. and -0.172 in. Both ends of the elbow are connected to 59-in. lengths of 30-in. O.D., 0.500-in. nominal wall thickness straight pipe. Details are shown in Figure 1. Three load cases are considered:

1. Inplane bending due to a 30 K-lb force with no internal pressure
2. Inplane bending due to a 30 K-lb force with 400 psi internal pressure
3. Inplane bending due to a 30 K-lb force with 800 psi internal pressure

The material properties of the elbow used for the analyses were Young's modulus E of 30,000,000 psi and Poisson's ratio of 0.3.

Table 1 shows the nominal values of stress and rotation used to compute stress intensification factors and flexibility factors in this study.

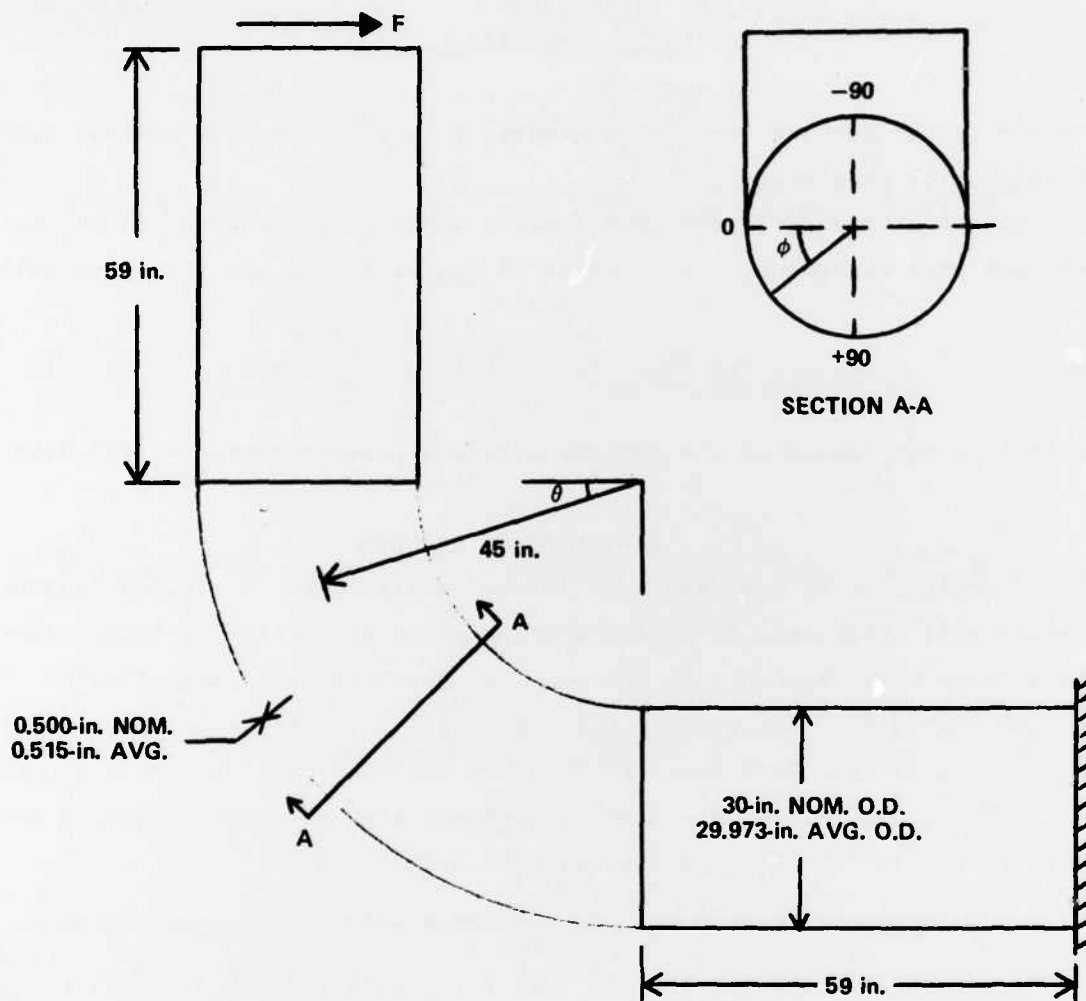


Figure 1 - Geometry of Pipe Elbow

TABLE 1. Nominal Values of Stress and Rotation For the Elbow

Pressure (psi)	Pr/t (psi)	Pr/2t (psi)	σ_{nom} (psi)	θ_{nom} (radians)
0.	0.	0.	5122.065	8.052965×10^{-4}
400.	11440.	5720.	5122.065	8.052965×10^{-4}
800.	22880.	11440.	5122.065	8.052965×10^{-4}

The finite element analyses were performed using the NASTRAN⁹ general purpose structural analysis program. For the first load condition, in which no internal pressure was applied, a straightforward static analysis (NASTRAN Rigid Format 1) was performed. For the remaining load cases corresponding to a pressurized elbow, static analyses with differential stiffness (Rigid Format 4) were performed.

The finite element discretization of the elbow and the tangent straight pipe extensions is shown in Figure 2. The end of one pipe extension was fixed, and the other pipe extension was ended with a rigid flange. The inplane force was applied to the rigid flange at the free end to produce the inplane bending load. Because of symmetry, only half of the circumference of the elbow cross section was modeled. The elbow and pipe extensions were modeled using NASTRAN's two-dimensional quadrilateral QUAD2 plate element with aspect ratios averaging near unity in the elbow region and about two near the ends of the pipe extensions. The model has 19 elements in the longitudinal direction of the elbow, 10 elements longitudinally in each tangent straight pipe extension, and 12 elements circumferentially (for 180 degrees) everywhere.

To compute flexibility factors, the average rotations of the cross sections at each end of the elbow were required. These averages were obtained in each cross section of interest by defining in that cross section an imaginary center point which was connected to the points on the circumference by beam elements flexible enough not to contribute significantly to the stiffness of the model.

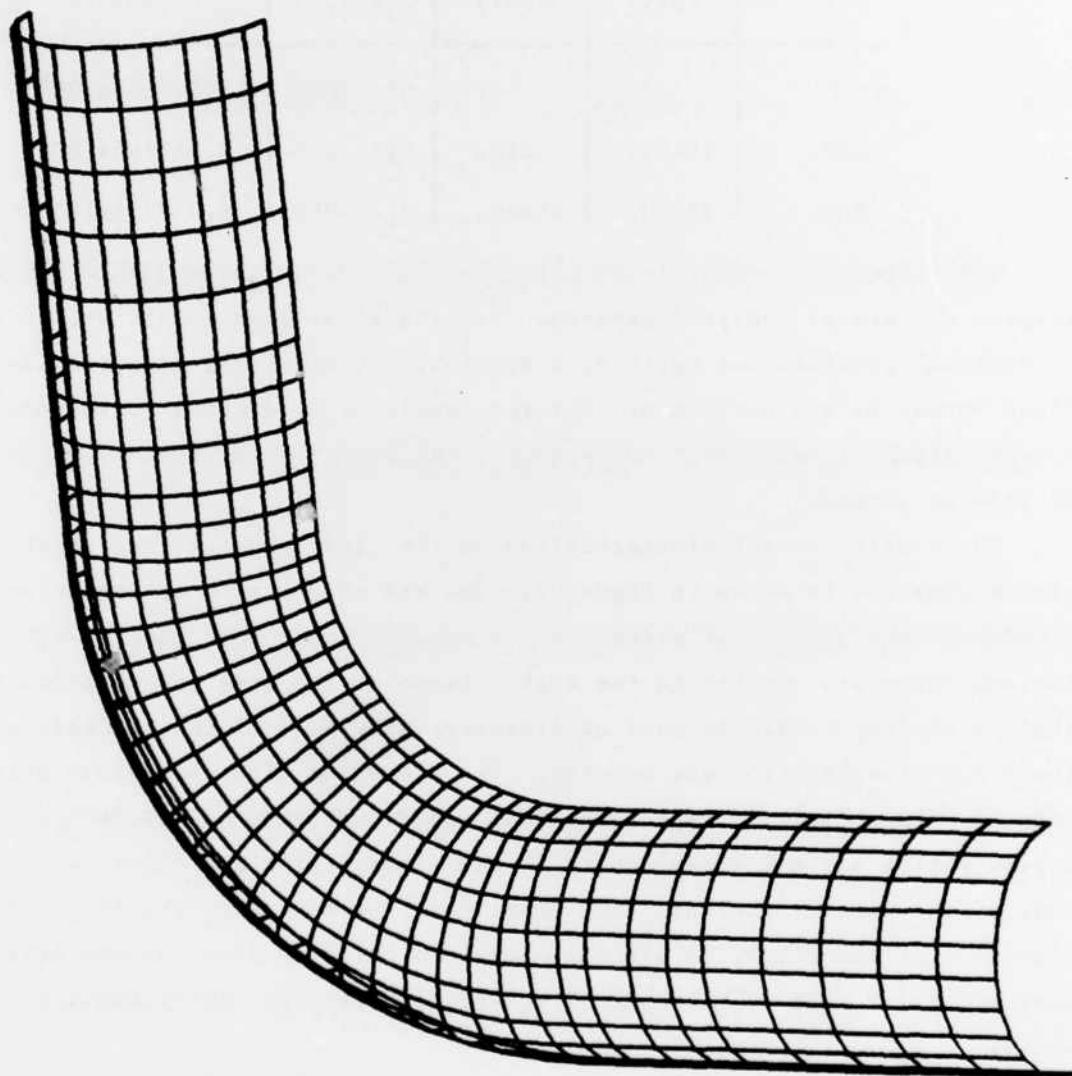


Figure 2 - Finite Element Model of Elbow

PRESENTATION OF RESULTS

Stress intensification factors were computed from NASTRAN stresses for a band of elements located at the middle ($\theta=45$ degrees) of the elbow. Flexibility factors were also computed from NASTRAN displacements of the cross sections at both ends of the elbow. These results are compared with experimental data in Table 2.

TABLE 2. Comparison of Test Results and NASTRAN Results

Test (Reference 2)				NASTRAN		
Pressure (psi)	Flexibility Factor	Maximum Stress Intensification Factor		Flexibility Factor	Maximum Stress Intensification Factor	
		circ.	long.		circ.	long.
0.	14.8	9.13	5.03	17.4	10.8	5.98
400.	11.1	6.08	3.70	13.3	6.85	3.86
800.	8.67	4.49	2.95	9.76	5.26	3.14

Figure 3 shows the distribution of stress intensification factors about the circumference of the cross section at the middle of the elbow. The NASTRAN data have been fitted by a cubic spline function^{10,11} resulting in the smoothed curves. Results for the 0, 400, and 800 psi internal pressure analyses are shown.

CONCLUSIONS

In general, flexibility factors and stress intensification factors computed from the NASTRAN finite element method agree reasonably well with the test data, although they tend to be conservative in slightly overestimating flexibility and stress intensification factors. These minor differences could perhaps be attributed to experimental factors such as nonuniform pipe wall thickness, strain gage spacing, and bending of tangent straight pipe extensions. However, these results are sufficiently accurate to verify that the finite element method is capable of analyzing the nonlinear effect of combining internal pressure with inplane bending of a 90-degree piping elbow.

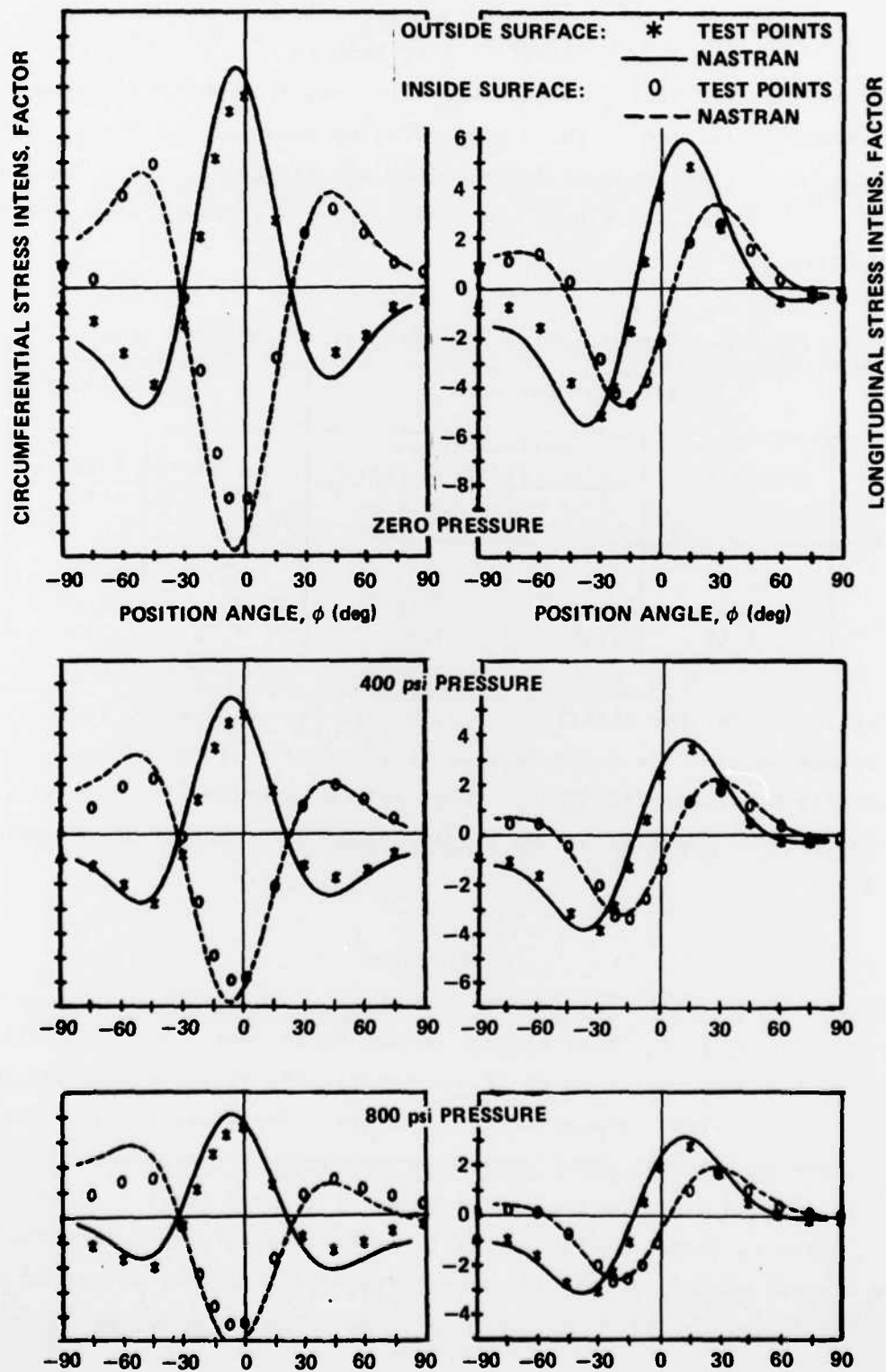


Figure 3 - Stress Distribution Around Circumference at Middle of Elbow

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